Sound exposure in harbour seals during the installation of an offshore wind farm: predictions of auditory damage

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Summary

1. With ambitious renewable energy targets, pile driving associated with offshore wind farm construction will become widespread in the marine environment. Many proposed wind farms overlap with the distribution of seals and sound from pile driving has the potential to cause auditory damage.
2. We report on a behavioural study during the construction of a wind farm using data from GPS/GSM tags on 24 harbour seals *Phoca vitulina* L. Pile driving data and acoustic propagation models, together with seal movement and dive data allowed the prediction of auditory damage in each seal.
3. Growth and recovery functions for auditory damage were combined to predict temporary auditory threshold shifts in each seal. Further, M-weighted cumulative Sound Exposure Levels [cSELs(M_{pw})] were calculated and compared to permanent auditory threshold shift exposure criteria for pinnipeds in water exposed to pulsed sounds.
4. The closest distance of each seal to pile driving varied from 4.7 to 40.5 km and predicted maximum cSELs(M_{pw}) ranged from 170.7 to 195.3 dB re 1μPa^2-s for individual seals. Comparison to exposure criteria suggests that half of the seals exceeded estimated permanent auditory damage thresholds.
5. Prediction of auditory damage in marine mammals is a rapidly evolving field and has a number of key uncertainties associated with it. These include how sound propagates in shallow water environments, and the effects of pulsed sounds on seal hearing; as such, our predictions should be viewed in this context.
6. *Policy implications*. We predicted that half of the tagged seals received sound levels from pile driving that exceeded auditory damage thresholds for pinnipeds. These results have implications for offshore industry and will be important for policy-makers developing guidance for pile driving. Developing engineering solutions to reduce sound levels at source, or methods to deter animals from damage risk zones, or changing temporal patterns of piling could potentially reduce auditory damage risk. Future work should focus on validating these predictions by collecting auditory threshold information pre- and post-exposure to pile driving. Ultimately, information on population-level impacts of exposure to pile driving is required to ensure that offshore industry is developed in an environmentally sustainable manner.

Introduction

Ambitious renewable energy targets have been developed to mitigate potential impacts of climate change (Jay 2010; Toke 2011). This has led to the proposed installation of several thousand wind turbines throughout coastal areas of Europe. Proposed wind farms are often located on offshore sandbanks, which are also important habitats for marine mammals. For example, harbour seals *Phoca vitulina* L. exhibit at-sea movements that overlap extensively with proposed wind farm locations in the North Sea (Sharples *et al.* 2012; Russell *et al.* 2014) and their distribution has been shown to be clustered around features such as offshore banks (Thompson 1993). This co-occurrence has led to concerns about the potential impacts of wind farms on marine mammals; concerns derive primarily from the production of intense impulsive sounds over periods of several months during impact pile-driving of turbine foundations (e.g. Madsen *et al.* 2006).

Underwater sound from pile driving has been measured in a limited number of studies (e.g. Bailey *et al.* 2010; Brandt *et al.* 2011); pulsed sounds are produced approximately every 1-2 seconds with predicted source levels ranging up to 250 dB re 1 $\mu Pa_{(peak\text{-}peak)}$ @ 1m (Bailey *et al.* 2010). The mammalian auditory system is likely to be vulnerable to damage from intensive sounds such as these and studies of auditory systems in mammals have shown that exposure to intensive pulsed sounds has the potential to cause elevated hearing thresholds (Henderson & Hamernik 1986; Kryter 1994; Finneran *et al.* 2000; Yost 2000; Finneran *et al.* 2002). Such threshold shifts can be described as either temporary (TTS) or permanent (PTS) depending on the capacity for post-exposure recovery (for review see: Clark 1991).

A number of studies on the effects of sound on the auditory system of harbour seals have been carried out (Kastak *et al.* 1999; Kastak *et al.* 2005; Kastelein *et al.* 2012). For example, Kastak *et al.* (1999) exposed harbour seals to 20 minutes of continuous octave band white noise with centre frequencies of 100, 500, 750, and 1000 Hz, at source levels 60 dB above the harbour seal hearing threshold (at the centre frequency); this resulted in an average 4.8 dB temporary decrease in hearing sensitivity (Kastak *et al.* 1999). Similarly, harbour seals exposed to octave-band white noise centred at 4 kHz (bandwidth 2.8–5.7 kHz) exhibited statistically significant TTS (>2.5 dB) when exposed to unweighted source levels of 136 dB re 1 μPa for 60 minutes and 148 dB re 1 μPa for 15min (Kastelein *et al.* 2012).

After a TTS, the time to recovery depends on the level of shift incurred; in general, the greater the shift, the longer the recovery period (Carder & Miller 1972; Mills, Gilbert & Adkins 1979). For example, the auditory sensitivity of a harbour seal with mean TTSs of 2 to 12 dB as a result of exposure to octave band white noise with a centre frequency of 2,500 Hz and net exposure durations of 22 min at 137 dB re 1 μPa @1m (which is equivalent to 80 dB above the hearing threshold of the seal at the centre frequency), and durations of 25, and 50 min at 152 dB re 1 μPa @1m (which is equivalent to 95 dB above the hearing threshold of the seal at the centre frequency), recovered fully within 24 h (Kastak *et al.* 2005). In a more recent study, a harbour seal was exposed for 60 minutes to an octave band white noise centred around 4 kHz with a considerably higher sound pressure level (SPL) of 163dB re 1 μPa (corresponding to 22–30 dB above levels causing TTS exceeding 2.5dB). This elicited a TTS of 44dB which only recovered after 4 days (Kastelein, Gransier & Hoek 2013).

Southall *et al.* (2007) developed an approach for evaluating the effects of anthropogenic sound on marine mammals. They developed a series of weighting curves based on the hearing characteristics of five functional marine mammal species groups and reviewed auditory damage studies to provide initial exposure criteria for pulsed and non-pulsed sounds. They predicted that for pinnipeds exposed to pulsed sounds underwater, the onset of PTS would occur at weighted cumulative sound exposure levels (cSELs) of 186 dB re 1 μPa^2-s (M_{pw}). For pinnipeds exposed to non-pulse sounds underwater, the predicted PTS onset threshold was at a weighted cSEL of 203 dB re 1 μPa^2-s (M_{pw}) (Southall *et al.* 2007). It is important to highlight that, due to the paucity of data on the effects of sound on marine mammal hearing, these preliminary exposure criteria of Southall *et al.* (2007) are based on assumed relationships between the relative levels of TTS and PTS which, in turn, involve proxy data from other species, and are intentionally conservative; further, they do not include the more recent data on auditory damage described above (e.g. Kastelein *et al.* 2012; Kastelein, Gransier & Hoek 2013).

Although hearing studies highlight the potential risks to marine mammals from acoustic exposure to pile driving, there is currently no empirical information on the at-sea proximity or the durations of exposure to pile driving, or movements and dive behaviour of seals during pile driving. Such information is critical to understanding the true risk of pile driving sound to seals. To address this gap, we carried out a harbour seal behavioural study during the construction of a wind farm in the North Sea. Our study used data from 24 animal-borne tags collected between January and July 2012. These tags provided location and dive data which, in combination with records of individual pile driving blows, allowed us to predict the potential for auditory damage in each seal.

Materials and methods

Study Area

The Lincs offshore wind farm is located on a submerged sandbank approximately 8 km off the coast of southeast England (53° 11.5' N, -0° 29.5' E). On completion, the wind farm consisted of seventy-five turbines located in water depths of approximately 8 to 20 m, and covering an area of approximately 39 km^2. As part of the wind farm construction, foundations (5.2m diameter steel monopiles) were installed between 14 May 2011 and 11 May 2012.

Pile driving

Throughout the period of this study (2 January–11 May 2012), 31 monopiles were installed using pile driving. Installation was carried out using a jack-up vessel with an MHU 1900S hydraulic hammer. The temporal pattern of pile driving was characterised by intermittent piling periods (~4–5 hours in length) followed by gaps from a few hours to a few days (Figure 1). Within individual pile installations, the median inter-strike interval was 2 seconds (SD=12 seconds) and the maximum blow energy was ~2,000 kJ per strike. A ramp-up procedure was carried out during all installations; in general, there was an increase from 100 to 700 kJ over the first 60 minutes before increasing to 2,000 kJ for the remaining installation. A total of 77,968 piling strikes were carried out during our study.

Telemetry

To measure the movements and proximity of seals at sea to pile driving, GPS/GSM tags (McConell *et al.* 2010) were deployed on 25 harbour seals in January 2012. Of these, three tags collected data for less than 2 days (and were therefore excluded from the dataset) with the other 22 collecting data for between 49 and 171 days (Table 1). Furthermore, two seals tagged during a concurrent study approximately 200 km to the south moved into the study area during pile driving and were included in the dataset. Therefore, data from 24 seals were used for further analyses.

Seals were captured whilst hauled out on intertidal sandbanks and were anesthetised with Zoletil® or Ketaset® in combination with Hypnovel®. The tags were attached to the fur at the back of the neck using Loctite® 422 Instant Adhesive. Capture and handling procedures are described in more detail by Sharples *et al.* (2012). All procedures were carried out under Home Office Animals (Scientific Procedures) Act licence number 60/4009.

The tags are data loggers that attempt to record the location of a seal at regular intervals using a hybrid GPS (Fastloc®) system. Stored location and dive data are opportunistically relayed ashore by means of an embedded mobile phone (GSM) modem. These tags provided seal locations approximately every 15 minutes. The data were cleaned and erroneous locations removed using thresholds of residual error and number of satellites; tests on land using these thresholds showed 95% of the cleaned locations had an error of <50m (Russell, Matthiopoloulos & McConell 2011). Further, dive data were provided as nine depth points distributed equally in time throughout each dive. During periods of pile driving, tracks of seals were interpolated linearly between successive GPS locations to provide estimated locations at one second intervals. Similarly, dive depths at each of these locations were estimated through linear interpolation between successive measured dive depths. These provided estimated 3D locations of each seal at one second intervals throughout periods of pile driving.

Acoustic exposure

To predict the acoustic exposure from pile driving for each seal, the source characteristics of the pile driving were derived from existing literature and a series of acoustic modelling approaches were carried out; these are described in Appendix S1 in the Supporting Information. Effectively, a median peak-to-peak source level estimated during previous pile driving at the same wind farm (Nedwell, Brooker & Barham 2011) was used as a source level for pile driving in this study; this value was then corrected for changes in pile driving hammer blow energy by relating individual piling stroke blow energy information (provided by the windfarm developer) with peak-to-peak received levels from recordings made with an autonomous moored sound recorder (DSG-Ocean Acoustic Datalogger; Loggerhead Instruments, FL, USA). This recorder was moored at a range of 4,900 m from the pile driving location. This information, together with information on the mean duration of a pile driving pulse and the mean difference between the peak-to-peak and root mean square sound pressure levels (SPL), was used to derive the Sound Exposure Level (SEL) of a pile driving single-pulse. Using these approaches, the pile driving was estimated to have a maximum single-pulse SEL of 211 dB re 1 μPa^2-s at the maximum blow energy of 2,000kJ.

Transmission loss across the study area was then estimated using range dependent acoustic models (Collins 1993); these are described in detail in Appendix S1 in the Supplemental Information. This was calculated along 5 degree radii from each of the pile driving source locations out to a range of 200 km. At each 1-km interval, transmission loss at a series of water depths was estimated; these were one metre and each 5 metre depth interval from 5 to 110 metres depth (the maximum seal dive depth during the study). The acoustic models were validated using boat based recordings during the installation of one of the piles; these recordings covered the full range of pile driving blow energies. Recordings were made using a Reson TC 4014 hydrophone with a Brüel and Kjaer amplifier (type 2635) and a calibrated Avisoft Ultrasoundgate 416 digital acquisition system at a sample rate of 192 kHz. Recording locations varied between 1,000 and 9,500 m from the pile driving.

Prediction of auditory damage

To predict the potential for auditory damage in each seal, received SELs for each pile driving pulse were estimated at the location of each of the seals using the approach described above; seal locations and depths were matched to the transmission loss estimates at the associated location and depth for each individual pile driving pulse to estimate received SELs (Figure 2 and 3).

Auditory damage was predicted in individual seals using two approaches. These were based on 1) results from previous studies of TTS onset, growth (during exposure), and recovery (post exposure) in harbour seals (e.g. Kastak *et al.* 2005; Kastak *et al.* 2007), and 2) the approach developed by Southall *et al.* (2007) for evaluating the likelihood of PTS in marine mammals exposed to anthropogenic sound (Figure 4).

The first approach required summing individual pulse SELs for each period of pile driving to calculate the cSEL and to integrate published TTS growth and recovery functions for harbour seals with the cSELs. The growth of TTS was modelled (Equation 1) as described by Kastak *et al.* (2005); the best fit parameter values for the harbour seal tested in their study were used to construct the growth curve in the present study. In the absence of data for harbour seals on recovery from TTS, recovery was modelled using a -8.8 dB per log(min) relationship for California sea lions *Zalophus californianus* L. (Kastak *et al.* 2007). It is important to highlight that predictions of auditory damage made here for pulsed sounds are based on TTS onset and recovery functions derived from exposure to octave-band (continuous) noise for varying durations.

(Equation 1)

$$TTS = (10m1)log_{10}\left(1 + 10^{((SEL-m2)/10)}\right)$$

where $m1$ is 2.0 and corresponds to the slope of the linear portion of the curve relating SEL to threshold shift (Kastak *et al.* 2005);

$m2$ is 183.1 and corresponds to the x intercept of the extrapolation of the linear portion of the curve (considered the onset of TTS (Kastak *et al.* 2005));

The second approach was to weight the SELs according to the auditory M-weighting function for pinnipeds in water (M_{pw}) formulated by Southall *et al.* (2007). For pile driving pulses, this effectively reduced individual pulse SELs by 1.6 dB re 1 μPa^2-s. M-weighted individual pulse SELs were then summed for each period of pile driving to calculate the cSEL (M_{pw}). Permanent auditory injury onset thresholds at a cSEL of 186 dB re 1 μPa^2-s (M_{pw}) for pinnipeds exposed to underwater pulsed sound within a 24-hour period were proposed by Southall *et al.* (2007); we therefore adopted this approach and calculated cSEL (M_{pw}) in each 24-hour period from the start of piling. In addition, Southall *et al.* (2007) propose an unweighted peak SPL of 218 dB re 1μPa as an alternative permanent auditory injury onset threshold. We therefore present predicted received peak SPLs (calculated as predicted SPL $_{\text{(peak-peak)}}$ minus 6dB) for each seal.

Given that the acoustic propagation model validation recordings were only made to ranges of ~10 km from the pile driving, there is greater uncertainty in the SELs and the characteristics of the signals (e.g. frequency, duration, rise time) received at seals beyond this range. To account for this, auditory damage predictions are summarised for cases where seals were within 10 km and beyond 10 km from the pile driving location.

Results

Telemetry

Throughout the study, all seals moved between haul out sites and areas offshore. During transits offshore, seals travelled within 20 km of the wind farm site. All seals spent time offshore during at least one pile driving event; the closest distance of individual seals to active pile driving locations while at sea varied between individual seals from 4.7 to 40.5 km.

Acoustic exposure

The results of the validation recordings suggested that the modelling approaches provided a relatively accurate means of predicting received levels from pile driving; overall mean error in the predictions of unweighted single pulse SELs was +2.3 (SD = 1.8) dB up to ranges of ~10 km from the source.

Maximum predicted unweighted single pulse SELs at individual seals varied from 146.1 to 166.5 dB re 1 μPa^2-s. In general, predicted received levels increased with dive depth; the maximum single pulse SEL was 166.5 dB re 1 μPa^2-s for seal 'pv42-277-12' at a range of 6.9 km and a dive depth of 17.1 m.

Prediction of auditory damage

Using the TTS growth and recovery functions established for exposure to continuous noise (Kastak *et al.* 2005; Kastak *et al.* 2007), it was predicted that all seals received SELs sufficient to cause TTS during pile driving. Predicted maximum threshold shifts for individuals ranged from 1.6 to 23.0 dB (Figure 5 and Table 1). Predicted cSELs (M_{pw}) (Southall *et al.* 2007) from pile driving varied between individual seals; the seal with the lowest exposure had cSELs (M_{pw}) ranging from 132.8 to 190.6dB re 1 μPa^2-s (M_{pw}), and the seal with the highest exposure had cSELs (M_{pw}) ranging from 147.2 to 195.3 dB re 1 μPa^2-s (M_{pw}) (Figure 6 and Table 1). In total, twelve (50%) of the seals were predicted to receive cSELs (M_{pw}) that exceeded the estimated PTS onset threshold of 186 dB re 1 μPa^2-s (M_{pw}) for pinnipeds in water exposed to pulsed sounds (Southall *et al.* 2007). The number of times these twelve seals exceeded the threshold varied between one and nine (Table 1).

Out to ranges where the acoustic propagation models were formally validated (~10 km), a total of five seals were present during pile driving with closest approaches ranging from 4.7 to 9.8 km from the pile driving location. Predicted maximum threshold shifts for these five seals ranged from 0.8 to 24.5 dB (Table 1). Of these five seals, three (60%) were predicted to exceed the estimated PTS onset threshold for pinnipeds in water exposed to pulsed sounds (Southall *et al.* 2007) between one and nine times (Table 1).

Discussion

This study used animal movement and dive data to predict the long-term acoustic exposure history of a marine mammal during the construction of an offshore wind farm. The results showed that all 24 tagged seals were present at sea and showed diving behaviour during pile driving at some stage during the study; we therefore predicted that each received acoustic exposure from the piling. The closest distance that each seal came to active pile driving locations varied between 4.7 and 40.5 km, and a total of 5 (~20%) of the seals moved within 10 km of pile driving.

Predicted received SELs were frequently relatively high and led to auditory damage predictions using both the approaches taken here. By integrating auditory damage growth and recovery functions established for exposure to continuous, octave-band noise (Kastak *et al.* 2005; Kastak *et al.* 2007), all seals were predicted to receive cSELs sufficient to cause TTS; although this was relatively low in three of the seals (<6 dB), the majority of seals (21 out of 24) were predicted to get TTS greater than 6dB, and two seals were predicted to get high levels of TTS (>20dB).

Using the M-weighted cSELs and the PTS onset criteria for pulsed sounds (Southall *et al.* 2007), half of the seals were predicted to gain PTS; furthermore, this was a relatively frequent occurrence (up to nine occasions) for some of the seals. The accurate prediction of auditory damage in this study is reliant on the thresholds being appropriate for pile driving sound; there are a number of important caveats and uncertainties that need to be considered with respect to this. The PTS onset thresholds as derived by Southall *et al.* (2007) are based upon assumed relationships between relative levels of TTS and PTS and are intentionally conservative. In their study, PTS was predicted if the auditory threshold was increased by ≥40 dB (i.e., 40 dB of TTS) (Southall *et al.* 2007). Although few studies of PTS in harbour seals exist, one study supports this assumption (Kastak *et al.* 2008). In their study, Kastak *et al.* (2008) twice exposed a single harbour seal to a 4.1 kHz pure tone with a maximum received SPL of 184 dB re 1 μPa for a duration of 60 s (SEL=202 dB re 1 μPa^{2}s). This led to a threshold shift in excess of 50 dB at 5.8 kHz, and an apparent PTS of 7 to 10 dB evident after more than two months following exposure (Kastak *et al.* 2008). In contrast, more recent work showed despite a high SPL exposure that resulted in 44 dB TTS in a harbour seal, full hearing recovery occurred within four days (Kastelein, Gransier & Hoek 2013). Thus, our predictions of PTS following Southall *et al.* (2007) will need further investigation once PTS thresholds for harbour seals are more fully understood.

TTS growth and recovery functions (Kastak *et al.* 2007) were derived from TTS measurements as a result of exposure to continuous sound. For these to be appropriate for pulsed sounds, we have assumed that TTS follows the equal energy hypothesis (Burns & Robinson 1970), i.e. that fatiguing sounds with equal SELs are predicted to induce the same TTS. However, recent results suggest that this may not be an optimal model for predicting TTS in harbour seals; both Kastak *et al.* (2005) and Kastelein *et al.* (2012) show that different levels of TTS may result from exposure to sounds with similar SELs, but consisting of different duration/level combinations. Kastelein, Gransier and Hoek (2013) suggest that their results are more in line with the hypothesis of Henderson *et al.* (1991) that hearing loss depends on the interaction of several factors including exposure level and duration, rise time, and repetition rate (Henderson & Hamernik 1986; Henderson *et al.* 1991). Similarly, studies of terrestrial mammals generally conclude that impulse noise is more hazardous than continuous noise with respect to hearing damage (e.g. Sulkowski & Lipowczan 1982; Dunn *et al.* 1991). For example, chinchillas exposed to pulsed noise showed substantially more threshold shift than a control group exposed to continuous pink noise (where signals were matched by exposure duration and $SPL_{(RMS)}$) (Dunn *et al.* 1991). Furthermore, Buck (1982) examined the effect of impulse rate on Guinea pigs *Cavia porcellus* and showed that TTS was greatest at a presentation rate of 1 per second and could be reduced by either increasing or decreasing this rate (Buck 1982). Price (1974; 1976) measured TTS in the domestic cats *Felis catus* after exposure to intermittent and continuous tones; results showed that recovery of TTS began within milliseconds of the end of exposure and continued for several hours. However, the presentation of tones intermittently effectively disrupted the recovery mechanism and led to longer recovery post exposure compared to continuous exposure (Price 1976).

The disparity in TTS growth between impulse and continuous noise exposures can also be seen in TTS patterns post exposure. Experiments on monkeys (Luz & Hodge 1970), humans (Fletcher 1970), and chinchillas (Hamernik, Patterson & Salvi 1987) have shown that post-exposure recovery from impulse noise often follows a non-monotonic pattern; i.e. there can be a post-exposure growth in TTS to maximum levels as much as 10 h after exposure (Hamernik, Patterson & Salvi 1987). This recovery pattern is markedly different from the typical log-linear recovery seen following continuous noise exposure (Ward et al., 1959).

Prediction of auditory damage is further complicated by uncertainties in the nature of the pulsed sounds of pile driving. First, it is important to highlight that the received levels in this study are derived from a series of acoustic models with associated assumptions; however, the sound propagation models used here have been benchmarked previously (e.g. Matthews & MacGillivray 2013) and are widely employed in the acoustics community. Furthermore, our validation suggests that the models provide an accurate means of predicting received levels out to at least 10 km from the pile driving. Nevertheless, we measured a mean error in single pulse SEL of +2.3 dB re 1 μPa^2-s (a positive value represents an overestimate); in terms of auditory damage prediction, if we incorporate this error into the predictions, all seals were still predicted to receive relatively high exposure but the number of seals exceeding the PTS onset threshold for pulsed sounds (Southall *et al.* 2007) reduces from twelve to seven. Similarly, predicted maximum threshold shifts for individuals reduce from between 1.6 and 23.0 dB (Table 1) to between 0.5 and 18.9 dB when this error is incorporated.

A second important point is that pulsed sounds are described as brief, broadband, atonal, transients, characterised by a relatively rapid rise time from pressure to maximal pressure (Southall *et al.* 2007). As Southall *et al.* (2007) highlight, a sound that has pulsed characteristics at the source may, as a result of propagation effects, lose those characteristics (e.g. rise time) and could be characterized as non-pulses at some (variable) distance from source. This has implications for the use of the Southall *et al.* (2007) pulsed threshold, particularly for exposures where the seals were a long distance from the pile driving. Rise times for the pile driving signals in our recordings were generally short. but did increase from around 35 to 100 msec between 1 and 10 km from the source; these appear to be within the range of rise times previously measured in industrial pulsed sounds (e.g. Źera 2001) and it would therefore seem valid to use the pulsed threshold in our study out to at least 10 km. This would support our prediction that of the five seals within 10 km of pile driving, three exceeded the PTS onset threshold for pulsed sounds (Southall *et al.* 2007). However, at longer ranges, it is arguable that the pile driving signals may no longer be considered impulsive and the nonpulse PTS threshold criteria for pinnipeds (cSEL: 203 dB re: 1 μPa^2-s) may be more appropriate; using this approach, none of the seals beyond 10 km from the pile driving would have exceeded the PTS threshold.

Although there are uncertainties associated with the predictions made here, using current published auditory damage thresholds for pinnipeds exposed to pulsed sounds, half of the seals were predicted to exceed the PTS onset threshold (Southall *et al.* 2007). The biological consequences of a permanent reduction in auditory sensitivity are unclear; however, underwater hearing is likely to be important for seals in a number of behavioural contexts. For example, low frequency vocalisations appear to play a role in reproduction (Van Parijs, Hastie & Thompson 2000) in harbour seals. These are produced by male seals and appear to function in male–male competition or advertisement to females (Hanggi & Schusterman 1994; Van Parijs, Hastie & Thompson 2000). Impairment to auditory sensitivity may therefore affect the detection of vocalisations with implications for reproductive success.

In addition to intraspecific communication, detection of underwater sounds is also important during foraging or for predator detection in some species; for example, utilization of prey sounds for hunting has been shown for several fish species (Myrberg 1981), and some cetaceans (Gannon *et al.* 2005) and seals (Stansbury *et al.* 2015) make use of passive listening during foraging. Furthermore, seals acoustically detect and avoid predators such as killer whales (Deecke, Slater & Ford 2002). Overall, based on psychophysical data (e.g. Wolski *et al.* 2003; Bodson *et al.* 2006; Reichmuth *et al.* 2013) and the allocation of resources to the auditory sense (Alderson, Diamantopolous & Downman 1960; Walloe *et al.* 2010) hearing appears to be important to seals and it seems likely that auditory impairment has the potential to impact individual fitness.

In summary, although the effects of pulsed sound on the auditory system are highly complex and the prediction of auditory damage in marine mammals is a rapidly evolving field of research, based on current noise exposure criteria (Southall *et al.* 2007), we predict that half of the seals received sound levels sufficient to exceed PTS thresholds during the construction of an offshore wind farm. A critical avenue for future work will be to validate the predictions made here through the collection of auditory threshold information pre- and post- exposure to pile driving; this could be carried out on wild seals using auditory evoked potential measurements (Wolski *et al.* 2003) or in a captive environment using controlled exposures and psychophysical methods (e.g. Kastak *et al.* 2005; Kastelein *et al.* 2012). Furthermore, although all seals remained in the general area during the study, it will be important to determine whether individual seals responded to piling to limit their acoustic exposure. This could potentially occur through spatial avoidance of areas with high received levels, or by animals actively changing hearing thresholds in response to noise to protect their auditory system (as is known from humans, bats and cetaceans: see Nachtigall & Supin 2013). Ultimately however, to estimate the population level impacts of exposure to sounds from activities such as pile driving , the long term impacts of auditory damage on individual fitness, fecundity, and survival need to be quantified (Thompson *et al.* 2013); such information is required to ensure that the development of offshore industry is carried out in an environmentally sound manner.

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Data accessibility

- Location and diving data for individual seals are available from the Dryad Digital Repository: doi: 10.5061/dryad.h79q4 Data files: pv42_data (Hastie *et al*. 2015)
- Pile driving data are the property of Centrica Energy Renewables, Millstream, Maidenhead Road, Windsor, Berkshire, SL4 5GD

Supporting Information

Supporting information may be found in the online version of this article.

Appendix S1: Estimation of acoustic exposure in seals

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Tables

Table 1: Summary of the predicted auditory damage for the tagged seals, including the maximum cSEL (M_{pw}) (dB re: 1 μPa^2-s) (Southall *et al.* 2007), the number of piling bouts where the PTS onset threshold was exceeded, and the maximum TTS (dB) predicted from TTS growth and recovery functions (Kastak *et al.* 2005; Kastak *et al.* 2007). Each of the predictions is shown for seals when located less than and greater than 10 km from the piling location

Seal ID	Sex	Age class	Tag duration (days)	Closest range to piling (km)	Maximum RL (dB re 1μ$Pa_{(peak)}$)	Max cSEL (M_{pw}) (dB re: 1 μPa^2-s)		# of piling bouts exceeding 186 dB re: 1 μPa^2-s		Max predicted TTS (dB re 1μPa)	
						<10km	>10km	<10km	>10km	<10km	>10km
pv40-268-12	Female	Adult	135	6.1	179.7	187.8	188.4	3	2	7.9	16.8
pv40-270-12	Male	Adult	91	40.5	171.0	-	178.6	-	0	-	2.9
pv42-162-12	Female	Adult	160	9.8	179.9	170.7	190.0	0	4	0.8	18.3
pv42-165-12	Female	Juvenile	64	6.9	173.5	182.0	185.5	0	0	1.9	8.2
pv42-194-12	Male	Adult	115	27.0	173.8	-	183.1	-	0	-	7.8
pv42-198-12	Male	Adult	131	29.1	179.0	-	187.1	-	3	-	14.0
pv42-220-12	Male	Adult	144	34.3	177.2	-	186.2	-	0	-	11.2
pv42-221-12	Male	Adult	50	26.8	173.3	-	183.6	-	0	-	7.8
pv42-266-12	Female	Adult	84	11.1	177.0	-	185.5	-	0	-	7.8
pv42-277-12	Female	Adult	158	4.7	184.7	193.4	191.3	9	3	24.5	21.2
pv42-287-12	Male	Adult	18	38.8	164.4	-	176.7	-	0	-	1.6
pv42-288-12	Female	Adult	170	15.8	176.1	-	185.5	-	0	-	11.9
pv42-289-12	Male	Adult	79	27.6	172.3	-	183.3	-	0	-	8.1
pv42-290-12	Female	Adult	58	16.9	175.6	-	187.8	-	1	-	9.5
pv42-291-12	Female	Adult	109	15.0	178.0	-	183.8	-	0	-	9.7
pv42-292-12	Male	Adult	105	31.5	174.8	-	184.3	-	0	-	5.2
pv42-293-12	Female	Adult	69	17.1	177.5	-	185.4	-	0	-	10.5
pv42-294-12	Male	Adult	103	29.6	172.7	-	184.0	-	0	-	8.9
pv42-295-12	Female	Adult	69	10.8	181.0	-	190.7	-	1	-	16.4

pv42-316-12	Male	Juvenile	106	5.8	179.1	184.3	187.4	0	1	6.6	13.3
pv42-317-12	Female	Adult	111	17.1	179.6	-	190.6	-	3	-	16.8
pv42-318-12	Female	Adult	139	13.8	180.6	-	195.3	-	7	-	23.0
pv42-319-12	Male	Juvenile	114	27.3	176.6	-	188.9	-	2	-	15.7
pv42-320-12	Female	Adult	106	4.9	182.3	188.7	186.0	1	1	17.3	12.5

Figures

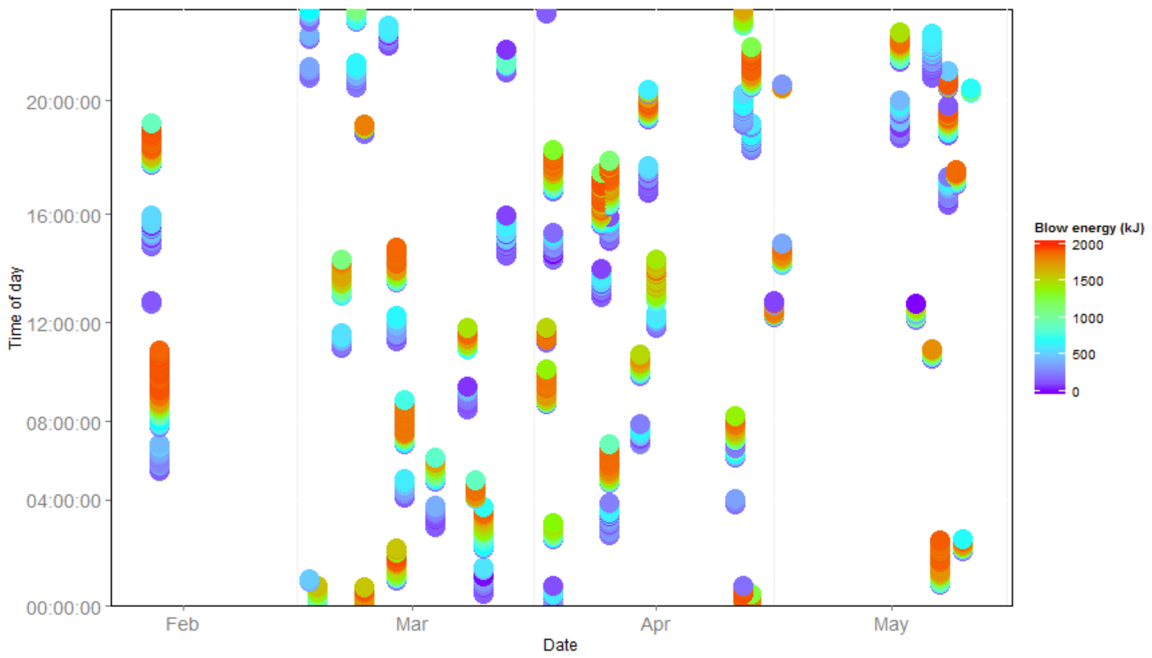

Figure 1: Temporal pattern in pile driving with month along the x-axis and time of day on the y-axis. Each point represents a pile driving pulse which is coloured by the blow energy (kJ) of the piling strike.

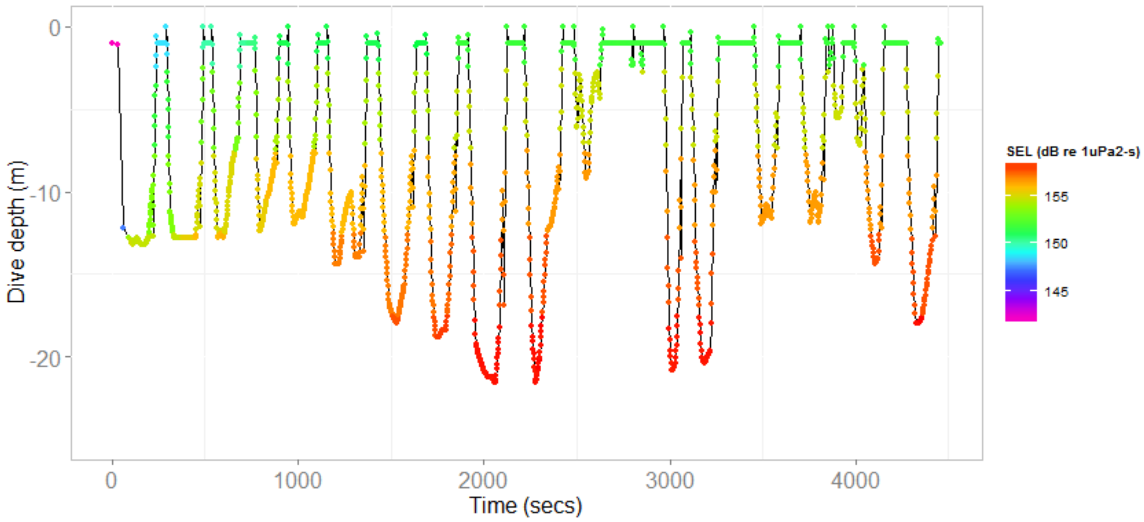

Figure 2: Example of a harbour seal dive profile over a period of 75 mins with predicted unweighted single pulse SELs (dB re: 1 μPa²-s) received from pile driving.

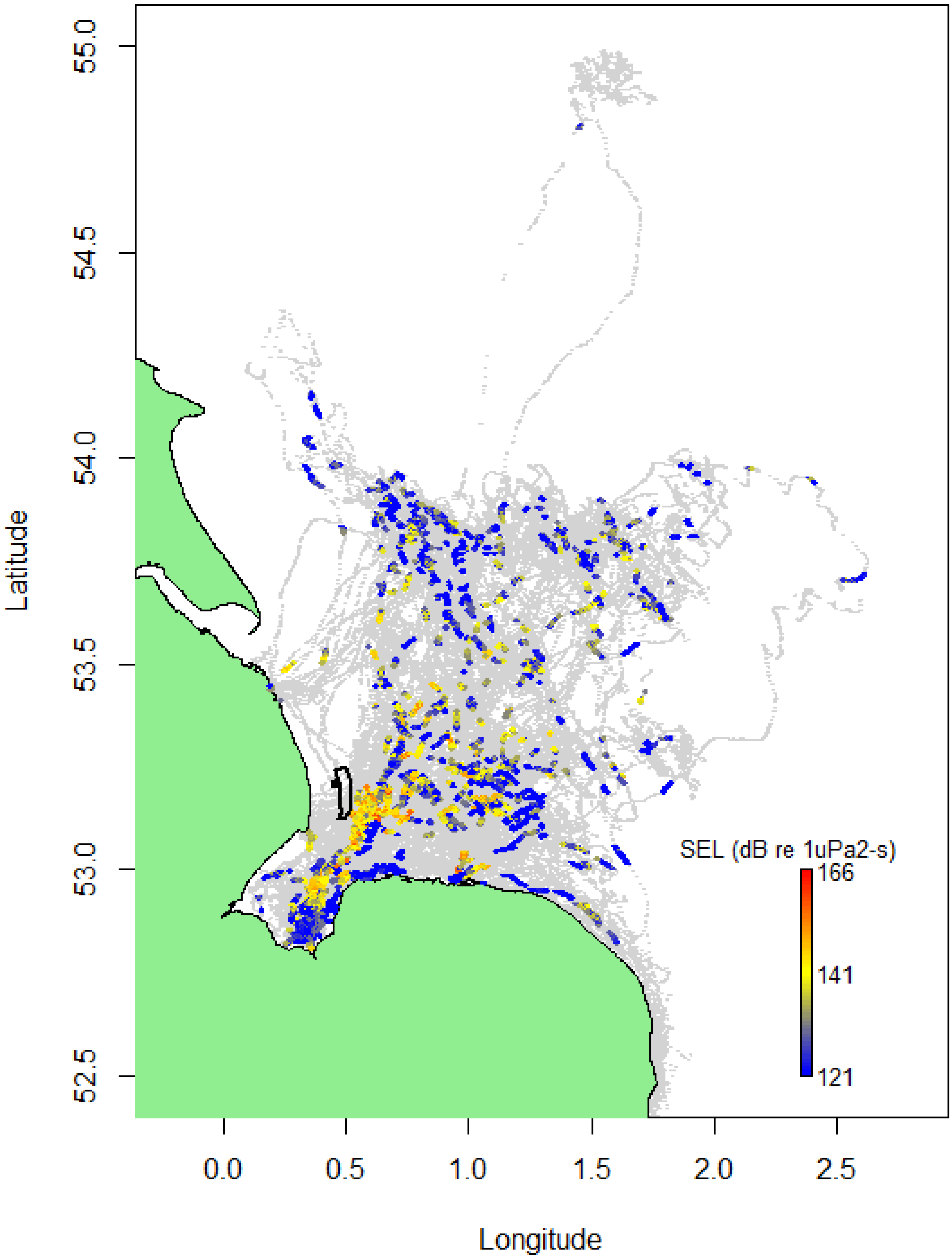

Figure 3: Map of the study area showing all GPS locations of 24 seals with predicted single pulse SELs (dB re: 1 μPa^2-s) from pile driving. The figure shows the seal locations when no piling was taking place (grey points), during piling (coloured points), and the location of the wind farm (black polygon).

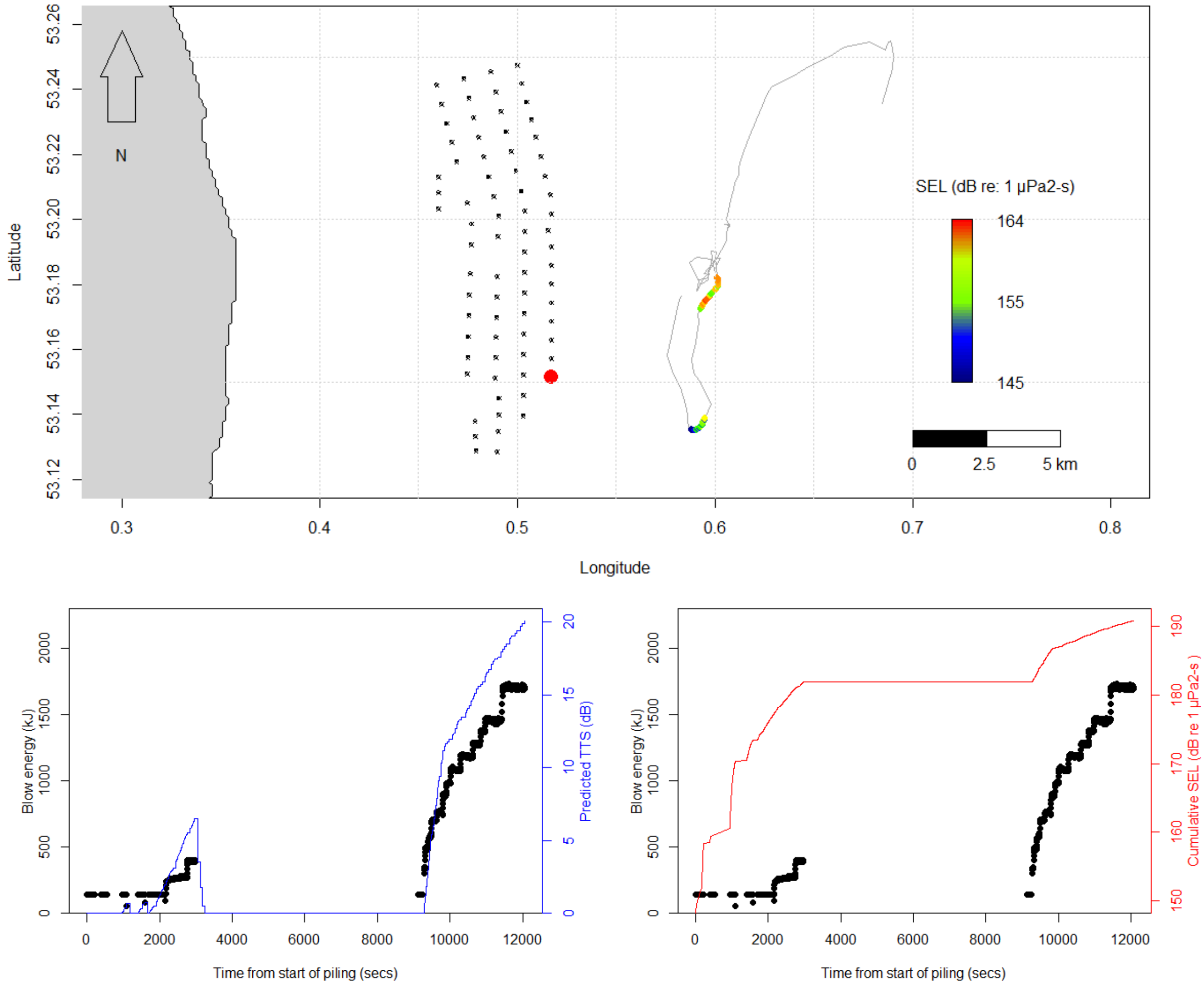

Figure 4: Example of the movements and corresponding auditory damage predictions in a harbour seal during pile driving. The top panel shows the track of seal pv42-277-12 (grey line) during a 24hr period, its locations during pile driving (coloured by predicted received unweighted SELs), the wind turbine foundations (black stars), and the pile driving location (red point). The lower panels show the timeline of the pile driving with associated blow energy (kJ) of the piling strokes (black points). The left also shows the predicted growth and recovery of TTS (Kastak *et al.* 2005; Kastak *et al.* 2007) (blue line) and the right shows the predicted M-weighted cSEL (dB re 1 μPa^2-s) (Southall *et al.* 2007) (red line).

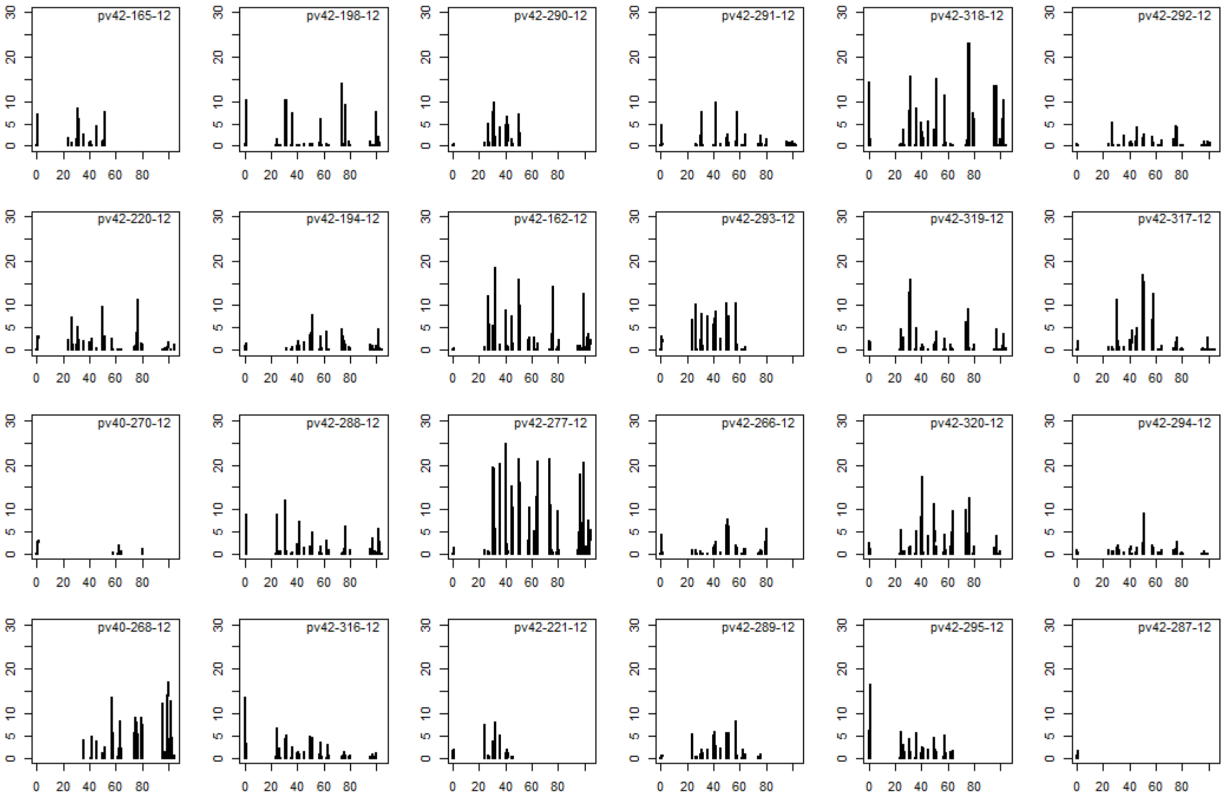

Figure 5: Predicted TTS (dB) for each seal based on functions established for exposure to continuous, octave-band noise (Kastak *et al.* 2005; Kastak *et al.* 2007). Each panel shows time along the x-axis (days) and predicted TTS on the y-axis for each seal.

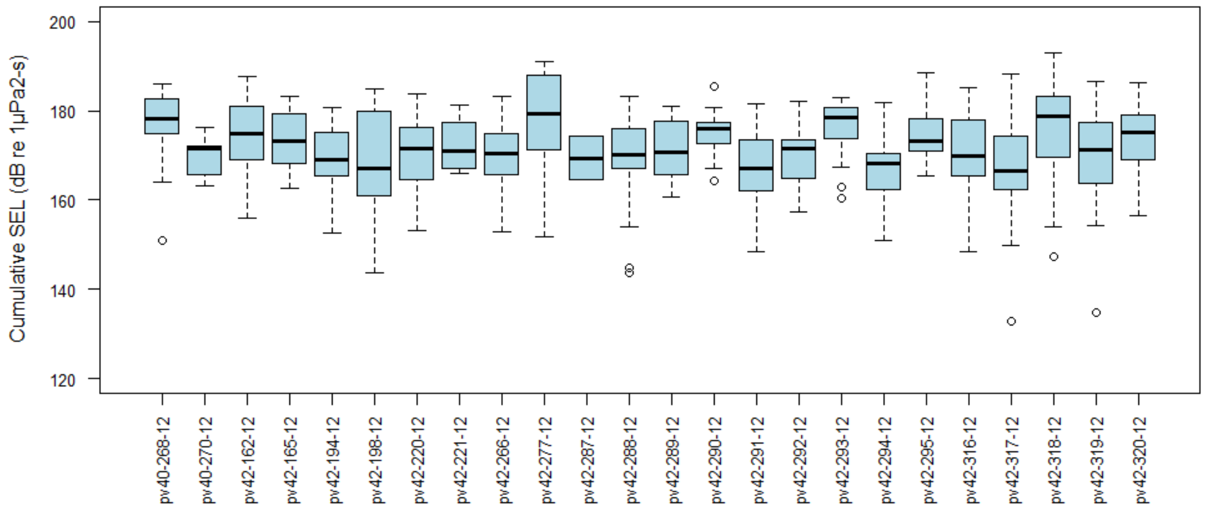

Figure 6: Summary of the M-weighted cSELs (M_{pw}) (dB re: 1 μPa^2-s) for individual seals. The figure shows cSELs (M_{pw}) in 24hr periods with the median value (solid line), the 25th and 75th percentiles (grey boxes), the range without outliers (whiskers), and outliers (open circles).